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Implementation of software programmable radios to form ad-hoc meshed networks to enhance maritime interception operations

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http://hdl.handle.net/10945/5225

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

IMPLEMENTATION OF SOFTWARE PROGRAMMABLE RADIOS TO FORM AD-HOC MESHED NETWORKS TO ENHANCE MARITIME INTERCEPTION OPERATIONS

by

Christopher Allen Vann

September 2010

Thesis Advisor: Alex Bordetsky
Second Reader: Carl Oros

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REPORT DOCUMENTATION PAGE				*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2010	**3. REPORT TYPE AND DATES COVERED** Master's Thesis
4. TITLE AND SUBTITLE Implementation of Software Programmable Radios to Form Ad-Hoc Meshed Networks to Enhance Maritime Interception Operations		**5. FUNDING NUMBERS**
6. AUTHOR(S) Christopher Allen Vann		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000		**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A		**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

Maritime Interception Operations have become a core competency for United States naval vessels working in conjunction with coalition units in remote waters. An increased need for real-time communication networks exists that will bring VBSS and SOC Teams in contact with experts who can determine the urgency and threat levels of vessels at sea and possible targets on land. The ultimate objective is to deliver timely intelligence, surveillance, and reconnaissance necessary to achieve situational awareness by tactical and strategic decision makers throughout the chain of command. The most critical aspect of this objective is to be able to provide seamless wireless coverage for littoral assets and to provide the security of data for sensitive information exchanged between multinational and coalition partners. The objective of this thesis is to evaluate and compare the suitability of ad-hoc wireless networks using software programmable radios in a maritime environment for employment in military and civilian security operations.

14. SUBJECT TERMS Ad-hoc, Wireless Networks, Software Programmable Radios, MIMO, Ultra-wideband, MIO, VBSS			**15. NUMBER OF PAGES** 59
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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Approved for public release; distribution is unlimited

IMPLEMENTATION OF SOFTWARE PROGRAMMABLE RADIOS TO FORM AD-HOC MESHED NETWORKS TO ENHANCE MARITIME INTERCEPTION OPERATIONS

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN INFORMATION SYSTEMS TECHNOLOGY

from the

NAVAL POSTGRADUATE SCHOOL
September 2010

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ABSTRACT

Maritime Interception Operations have become a core competency for United States naval vessels working in conjunction with coalition units in remote waters. An increased need for real-time communication networks exists that will bring VBSS and SOC Teams in contact with experts who can determine the urgency and threat levels of vessels at sea and possible targets on land. The ultimate objective is to deliver timely intelligence, surveillance, and reconnaissance necessary to achieve situational awareness by tactical and strategic decision makers throughout the chain of command. The most critical aspect of this objective is to be able to provide seamless wireless coverage for littoral assets and to provide the security of data for sensitive information exchanged between multinational and coalition partners. The objective of this thesis is to evaluate and compare the suitability of ad-hoc wireless networks using software programmable radios in a maritime environment for employment in military and civilian security operations.

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LIST OF ACRONYMS AND ABBREVIATIONS

BFC	Biometric Fusion Center
BIAC	Biometric Intelligence Analysis Reporting
CENETIX	Center for Network Innovation and Experimentation
COTS	Commercial Off-the-Shelf
CTF	Combined Task Force
DO	Distributed Operations
DoD	Department of Defense
$DOTC^2$	Distributed Operations Tactical Command and Control
EC08	Empire Challenge 08
EFT	Electronic Fingerprint Transmission
FFG	Guided Missile Frigate
FMV	Full Motion Video
FTP	File Transfer Protocol
GIG	Global Information Grid
GPS	Global Positioning System
HVT	High-Value Target
ISR	Intelligence, Surveillance, and Reconnaissance
JTRS	Joint Tactical Radio System
LOS	Line of Sight
MIO	Maritime Interception Operations
NOC	Network Operations Center
NPS	Naval Postgraduate School
ONI/NMCI	Office of Naval Intelligence—National Maritime Intelligence Center
OTC	Officer in Tactical Command
OTM	On-the-Move
PTT	Push-to-Talk
RA	Rescue and Assistance

SA	Situational Awareness
SDR	Software Defined Radio
SINCGARS	Single Channel Ground and Airborne Radio System
SME	Subject Matter Expert
SOA	Scene of Action
TFC	Task Force Commander
TNT	Tactical Network Topology
TOC	Tactical Operations Center
TRANSSEC	Transmission Security
UAS	Unmanned Aerial Systems
USCG	United States Coast Guard
USJFCOM	United States Joint Forces Command
USUSN	United States Navy
VBSS	Visit Board Search and Seizure
WND	Wireless Networking Device

ACKNOWLEDGMENTS

I would like to thank Dr. Alex Bordetsky, Carl Oros, Lt. Col., USMC (Ret.), and the entire CENETIX team for helping to bring this thesis to fruition. Without their help and guidance, I would not have been able to accomplish this momentous goal.

To my family and friends, I say thank you for your love, patience, and understanding in the long nights that took me away from you in completion of my goals.

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I. INTRODUCTION

A. BACKGROUND

> In 2008, 111 vessels were targeted by Somali pirates resulting in 42 hijackings. Whilst the number of 2009 incidents has almost doubled, the number of successful hijackings is proportionately less. This can be directly attributed to the increased presence and coordination of the international navies along with heightened awareness and robust action by the Masters in transiting these waters.[1]

In the past, the United States Navy (USN) has trained for and conducted Visit Board Search and Seizure (VBSS) operations as a supplement to its primary missions of protecting the sea lines of communication from being overpowered by other dominant world superpowers. VBSS began by having designated personnel aboard each ship who were considered as a "prize crew." Only a small amount of training was involved and the mission was rarely executed. Usually these prize crews would attend to Rescue and Assistance (RA) of smaller vessels stranded on the high seas. Some smaller vessels, such as frigates (FFGs), would assist the United States Coast Guard (CG) drug interdiction operations in the Caribbean Ocean. The vast majority of training and funding was used to train USN vessels in anti-air, anti-surface, and anti-subsurface warfare.

Modern-day piracy is very much unlike the romanticized stories of the golden age of piracy from the late seventeenth and eighteenth centuries. Contemporary films portray these pirates as misunderstood outcasts who live outside the laws and restrictions of the common man. The reality of these pirates were that they preyed upon lone vessels with very little to defend themselves. Commerce and trade interruption forced nations to seek out these rogue individuals actively and bring them to justice.

[1] Edward Lundquist, "The Entire Indian Ocean is Up for Grabs," *Proceedings* 126 (July 2010), http://www.usni.org/magazines/proceedings/story.asp?STORY_ID=.

A commonality among today's pirates and those of the past is that they still prey upon individual vessels largely incapable of defending themselves.

Piracy off the coast of Somalia has significantly increased the cost of shipping worldwide. "Pirates now operate in an estimated 1.4 million square miles of open waters off Somalia and Nigeria, another piracy hot spot on Africa's Atlantic Coast. Avoiding attacks can easily add $1.5 million to $2 million in extra fuel, time and labor to the cost of a shipment to Europe, but the cost of navigating such dangerous waters is higher still. Insurance premiums protecting against vessel damage and delays due to piracy have increased five- to tenfold."[2]

This increase in the cost of shipping has forced the international community to act. "Navies are working together in coalitions, such the Combined Maritime Forces counter-piracy unit, Combined Task Force (CTF) 151, and the European Union Task Force Atalanta that protects humanitarian shipments. And while traditional allies have worked together for years, there are new players. Russia, China, and Iran have ships in the area, too. China's navy is showing the flag for its first out-of-area deployment in 600 years. "There are up to 27 nations participating," said Burnett. "De-confliction is a crucial element. Some ships can't talk to each other by email. Others are using Morse code."[3]

Deconfliction of communications is critical for successful operations. A task force commander must have the ability to receive and disseminate information quickly from the Scene of Action (SOA). The on-scene Officer in Tactical Command (OTC) must be able to communicate with his VBSS team to determine if a suspect vessel must be detained or released. Time and resources are critical to both vessels. The cost of fuel and delay of its shipments obviously hurt the shipping company trying to transit its cargo from one port to another. The cost of transit, safety of teams, and time spent searching innocent shipping

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[2] Catherine Holohan, "The Real Cost of Piracy," *MSN Money,* April 14, 2009, http://articles.moneycentral.msn.com/Investing/Extra/the-real-cost-of-piracy.aspx.

[3] Lundquist, "The Entire Indian Ocean is Up for Grabs."

vessels takes the boarding ship away from the real threats to shipping. The TFC and OTC do not generally operate in the same area and are often thousands of miles away from each other operating in different parts of the world.

> Historically, small-unit leaders have relied upon voice radios with minimal data capability to receive the Commander's intent and execute missions. While this method of voice transmission has been adequate in the past, the complexity of the environment we now operate in has changed… they must have improved situational awareness (SA), increased bandwidth, and improved network services. In essence, they must be smarter and better informed than the enemy.[4]

It is absolutely necessary to provide information between the OTC and TFC in an efficient and correct manner. This thesis proposes the use of software programmable radios to be used by VBSS teams to form ad-hoc wireless mesh networks during boardings of suspect vessels that simultaneously allow the exchange of voice, video, data, and Global Positioning System (GPS) information to be shared in near real-time between the OTC, TFC, and Subject Matter Experts (SMEs).

Through a series of experiments conducted by the Center for Network Innovation and Experimentation (CENETIX) at the Naval Postgraduate School (NPS), software programmable radios were used in various scenarios upon land and sea.

B. TACTICAL NETWORKING TEST BED

> Supportive information technology solutions: We will leverage information and technology, and focus our investments in support of our personnel supply chain. The transition to a mobile and more dispersed workforce will require enhanced virtual collaboration

[4] Command and Control Integration Division (C2ID), Combat Operations Center (COC) Study Capability Set (CAPSET) V for Marine Corps Air-Ground Task Force (MAGTF) Command and Control (C2). Doctrinal Study, Marine Corps Combat Development Command (MCCDC), United States Marine Corps, Woodbridge: Computer Sciences Corporation, 2008, ES-1.

> techniques. These capabilities will be delivered by drawing from upon Department of Defense and Navy Enterprise IT investments and solutions.[5]

This vision of the U.S. Navy's leadership is being executed at the Naval Postgraduate School. The Center for Network Innovation and Experimentation (CENETIX) is a unique environment created by Dr. Dave Netzer and Dr. Alex Bordetsky.

Working with USSOCOM, OSD, and DHS S&T programs, these researchers started what is now known as Tactical Network Topology (TNT) experiments consisting of two areas of study.

The first area involves field experiments in which "NPS researchers and students as well as participants from other universities, government organizations and industry investigate various topics related to tactical networking with sensors and unmanned aerial systems (UAS) as well as collaboration between geographically distributed units with focus on high value target (HVT) tracking and surveillance issues."[6] These experiments are conducted quarterly at Camp Roberts, CA. Further, they help "to explore synergy and impact of emerging sensor-unmanned systems-decision maker sensor-unmanned systems-decision maker self-forming networks on to the HVT and ISR missions."[7]

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[5] Mark Ferguson III, Gary Roughead, and Dirk Debbink, *Navy's Total Force Vision for the 21st Century* (January 2010), 10.

[6] Alex Bordestky and Dave Netzer, "Testbed for Tactical Networking and Collaboration," *The International C2 Journal* 4, no. 3 (2010): 1–33.

[7] Ibid.

Large Interdisciplinary NPS Team

27 Thesis Students

31 Faculty, 4 Staff; 9 Departments and Institutes

Includes 21 PhDs

Course Projects: IS, OR, MET

28 NPS Field Experimentation Projects

Programs Utilizing TNT Testbed

AFRL JASMAD	JIEDDO
AFRL Marti	MCWL TW Radio
AFRL N-CET	Team TACLAN
AFSOC CP/BI	JFCOM EC-08

Participating Universities

ASU	Univ. of Bundeswehr - Munich
Carnegie Mellon	Univ. of Florida
Case	Virginia Tech
JHU/APL	WPI
MIT	WVHTF
NDU	UM, Columbia, UCSD, UCCS
UC Berkeley	

Figure 1. TNT Academic Participants for FY08.[8]

Foreign Country Participation in MIO

Univ. of Bundeswehr at Munich

Swedish Naval Warfare Center

Turkish Air Force Academy

Systematic/Danish Navy Training Center

Broad DoD and Gov't. Participation and Support

- USSOCOM	- USASOC
- AFSOC	- NAVSOC
- MARSOC	- JSOC

Other Participating DoD and U.S. Gov't.

AFRL	LLNL	SPAWAR
ARL	NAWCWD	TSWG
BTF	NECC	USASMDC
DARPA	NIST	USCG/D-11
DHS/S&T	NRL	USCG-Staten Island
DNDO	NSA	USMC-HQMC
DOE RAP	NSWCCD	USMC-MSTSSA
DTRA	ONR	USMC-MCWL
JFCOM	ONR 113	USATC (Fort Eustis)
JIEDDO	OPNAV N8F	
JITC	OSD/HD	
LBNL	OSD/RRTO	

National Guard

West Virginia – Camp Dawson

Indiana – Camp Atterbury

State and Local Government in MIO

Alameda County Sheriff's Office

Oakland Police Dept.

San Francisco Police Dept.

Port Authority of NY/NJ

Fire Department New York

California Office of Emergency Services

California Dept. of Health

U.S. Park Police

Figure 2. TNT Federal, Local, and Foreign Participants in 2008.[9]

[8] Bordestky and Netzer, "Testbed for Tactical Networking and Collaboration."

The entire network is considered a Plug-and-Play test bed connected to a worldwide network via a fixed wireless 802.16 backbone. Figure 3 illustrates the connected network with reach back to the east coast via the Network Operations Center (NOC) at NPS.

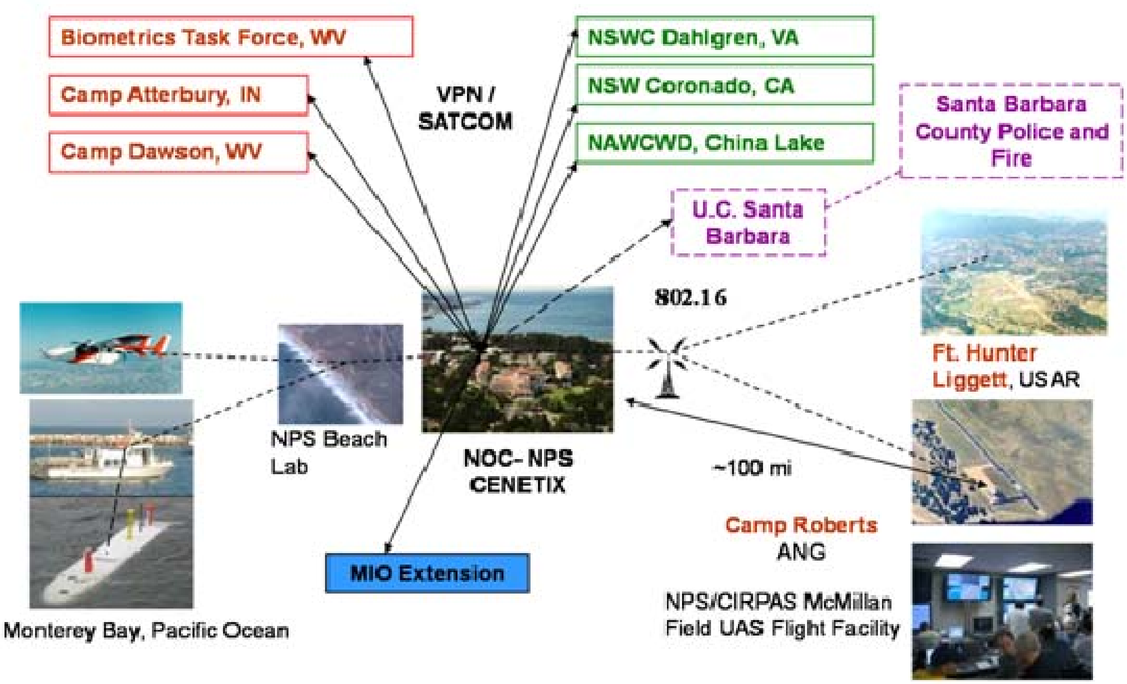

Figure 3. Plug-and-Play Testbed with Global Reachback: Camp Roberts Segment with Reachback to East Coast Centers.[10]

The second part of the experimentation concerns Maritime Interception Operations (MIO). In 2008, MIO scenarios were conducted in San Francisco, New York, New Jersey, and Virginia.

The MIO scenario focuses on the challenge of "searching large cargo vessels and interdicting small craft possessing a nuclear radiation threat."[11] Through a wireless network, boarding team members can send near real-time

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[9] Bordestky and Netzer, "Testbed for Tactical Networking and Collaboration."

[10] Ibid.

[11] Ibid.

data back to SMEs located in remote areas removed from the actual location of the boarding or interdiction. The nuclear radiation experts at the Lawrence-Livermore Labs located in California and the Biometric Fusion Center in West Virginia are two examples of these SMEs.

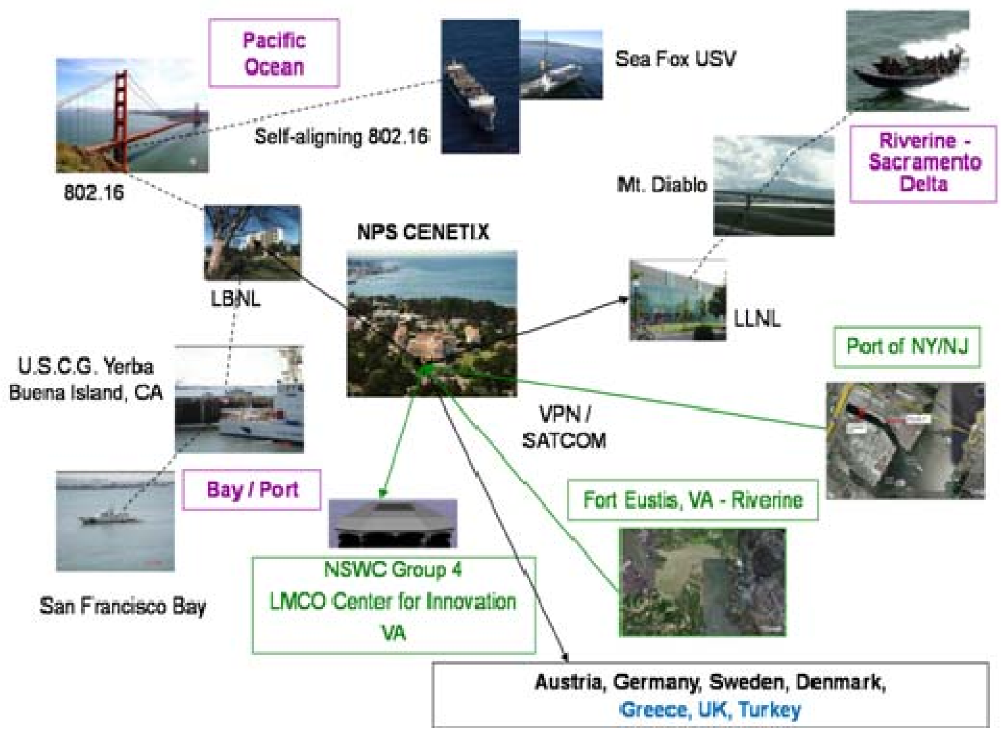

Figure 4. Plug-and-Play TNT MIO Testbed Segment: SF Bay, East Coast and Overseas.[12]

Through this network, nuclear detection and biometric data are collected by boarding party members. The data are remotely sent to the SMEs to be matched with known threat databases. The network has allowed for positive matches within four minutes,[13] which demonstrates one benefit of this worldwide distributed network. The boarding team and on scene commanders can make

12 Bordestky and Netzer, "Testbed for Tactical Networking and Collaboration."

13 A. Bordetsky, A. Dougan, C. Foo Yu, and A. Kihlberg, "TNT Maritime Interdiction Operation Experiments: Enabling Radiation Awareness and Geographically Distributed Collaboration for Network-Centric Maritime Interdiction Operations," *Defense Technology and Systems Symposium,* Singapore, December 5–8, 2006.

decisions while the team is still aboard the suspect vessel, which thus saves time and costs for both the boarding party and subject vessel. This greater decision-making capability decreases the amount of time a team spends aboard an innocent vessel and allows more time to pursue viable threats. The innocent suspect vessel saves valuable resources since it is not detained while data is being evaluated and reported back to the on-scene commander, and is thus, allowed to continue its transit.

C. SOFTWARE DEFINED RADIOS

The purpose of the experiments outlined in this thesis is to test a commercial off the shelf (COTS) solution to enhance information exchange between an on-scene operator and various command and control elements in support of maritime interdiction operations. The specific software defined radio used was the TrellisWare Technologies Inc. CheetahNet tactical network device, designated the TW220. This device has specifically been designed to overcome the challenges of forming a mesh network in the harshest RF environments. The TW220 can "offer networked digital voice, streaming video and IP data connectivity robustly across the following.

- Tunnels, caves, mines, and bunkers
- In and around buildings in dense urban area
- Cargo vessels to aircraft carriers
- Raised noise floor environments
- High dynamic environments such as aircraft and moving vehicles"[14]

The arduous environments in which the boarding teams operate require durable equipment able to function properly when needed. In remote locations, spare parts and technical support are sparse. The tools these personnel use must satisfy specific requirements as established by the Department of Defense (DoD). They must also be able to connect quickly and reliably with the Global Information Grid (GIG).

[14] Trellisware.com, "Harsh Environment Communication," http://www.trellisware.com.

The need for such a device as the TW220 has now been established, and the abilities advertised allow more efficient communication up and down the chain of command. A valuable solution is one that allows for all of this information to be sent at one time via one piece of equipment.

Table 1 lists the specifications for the TW220 and Figure 5 presents a diagram of the TW220.

FEATURE	BASELINE CONFIGURATION	SDR CUSTOMIZATION RANGE
Communication Range (Single Hop)	up to 5 miles in harsh multipath up to 20 miles in moderate multipath up to 100 miles LOS	up to 7 miles in harsh multipath up to 40 miles in moderate multipath up to 200 miles LOS
Transmit Power	<2 Watt Peak	Up to 20 Watt Peak
Supported Applications	Cellular quality PTT voice, streaming IP video, IP data	H.264 video, cellular quality full duplex voice
Aggregate Data Rate	Up to 3Mbps	Up to 12Mbps
Encrytion Security	AES-256	Same
Mobile Mesh Relay Hops (end-to-end latency)	3 hops (200 ms)	Up to 9 Hops (400 ms)
Voice Channels	8 Channels (7 plus one commandoverride channel), simulitaneous monitoring of multpile channels	0 to 64 channels
Operating Band	Dual Band (ISM and L-Band)	Single or Dual Band - turnable ranges
Frequency Bandwidth	4-20 MHz	Same
Antenna	Standard omni dipole	Embedded cellular omni, directional, and multi-antenna

Table 1. TW220 Specifications.[15]

15. Trellisware.com, "Wireless Networking Solutions," http://www.trellisware.com/products/wirelessnet.htm.

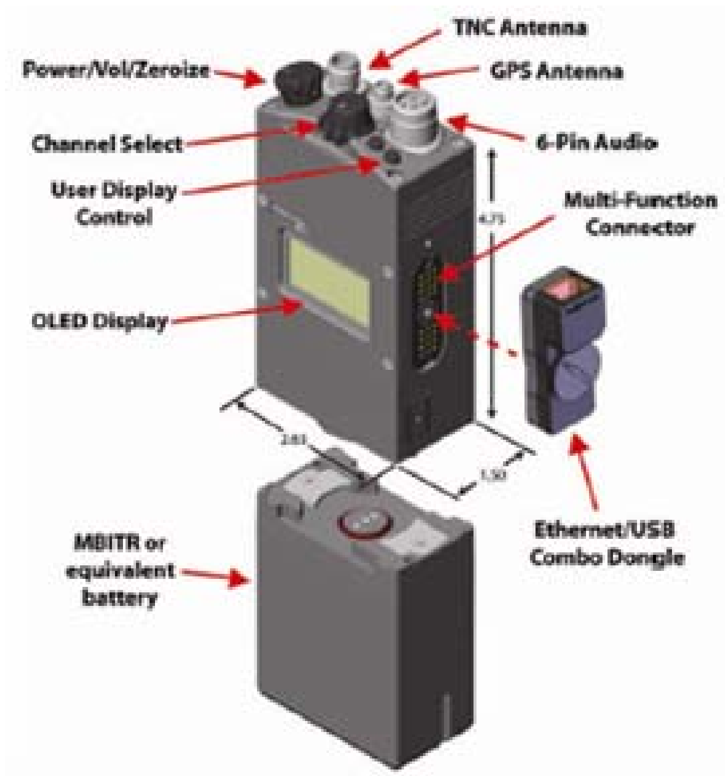

Figure 5. TW220 Diagram.[16]

The TW220s used within these experiments were initial prototypes. The vendors actively sought the opinions and provided feedback to the Naval Postgraduate School students who used them for the experiments in this thesis.

The specific questions this thesis attempts to answer are as follows.

D. RESEARCH AREAS OF CONCERN

MIO VBSS Teams want to see the following requirements within a handheld software defined radio.

- Tactical Voice Communication—The ability for all team members to be able to communicate with one another and with the Officer in Tactical Command (OTC).
- Video—The ability for each team member to send video back to the entire Chain of Command (COC) as a search of a suspect vessel is being conducted; for example, a USCG team searching for nuclear

[16] TW220 Users Manual v1.3.

devices upon a large merchant vessel at sea. Not all boarding team members are subject matter experts. The ability for the team member to be able to show experts visually, such as those employed to identify known threats, greatly enhances the effectiveness of the overall operation.

- Data—Biometric data is collected in individual files within collection devices. This data must be transported back to a NOC to be disseminated to various government agencies for database entry and identification. Time can be saved by automatically sending the data to these agencies as soon as they are collected. Other examples of data files that must be transferred are ship's manifests, crew logs, pictures of individual crew members, and suspect cargo.
- Personnel Location—An added safety consideration is the ability to track boarding team members as they search a large merchant vessel. An OTC can have greater situational awareness of each team member's location within a suspect vessel.
- Simplicity in design—Small handheld devices can greatly diminish the amount of equipment that VBSS Teams must bring aboard a suspect vessel. A durable waterproof design that is intuitive to operate is beneficial to overall operations.

Through controlled experimentation, the TW220 will be tested to see if it is a viable solution for the above criteria.

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II. MESH NETWORKS

A. AD HOC MESH NETWORKS

The need for instant peer-to-peer voice and data communication on a battlefield fueled the fire for the development of mesh networks. The ability to communicate without a fixed infrastructure greatly enhances the speed of maneuver for individual small units. There is no need for antennas or radio towers. Each soldier's individual radio would add another extension to the network. The more radios within a network, the more robust.

The advantages of a mesh network over a traditional wireless network are as follows:

- Meshing efficiently mitigates line-of-sight obstacles and RF interference issues: Multi-hopping enables voice, video, and data to be instantly routed around obstacles and interference. As, a result, mesh technology allows reliable, high-speed wireless networking in locations where it was never possible before: in crowded urban environments, massive buildings, subway tunnels, - virtually anywhere.
- Networks can be established and reconfigured automatically, instantaneously: Because nodes can automatically communicate to form networks with no manual configuration for small unit tactical operations that requires instant information access in any situation.
- Mesh Networks offer flexible deployment options: They can be built on permanent infrastructure or deployed quickly in ad hoc peer-to-peer architecture.
- Throughput can be optimized automatically, even over long distances and large networks: Relatively short radio links and dynamic load balancing mean that throughput can be optimized without regard to the radius of the network or the number of nodes. Performance tends to increase as additional nodes join. The same high bandwidth is available for both data uplinks and downlinks.[17]

Figure 6 demonstrates the mesh network's ability to extend and be robust.

[17] Motorola, *Mesh Networks Delivering IP-Based Seamless Mobility in Municipal and Ad Hoc Wireless Networks* (White Paper, 2006), 7.

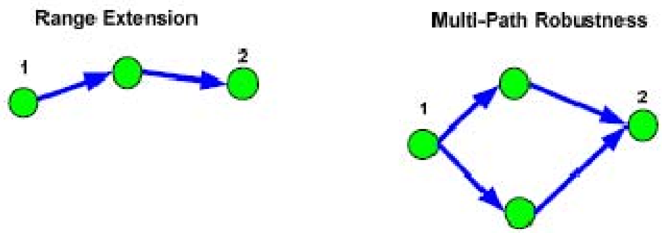

Figure 6. Relay Benefits.[18]

Figure 7 is an illustration of merging mesh networks.

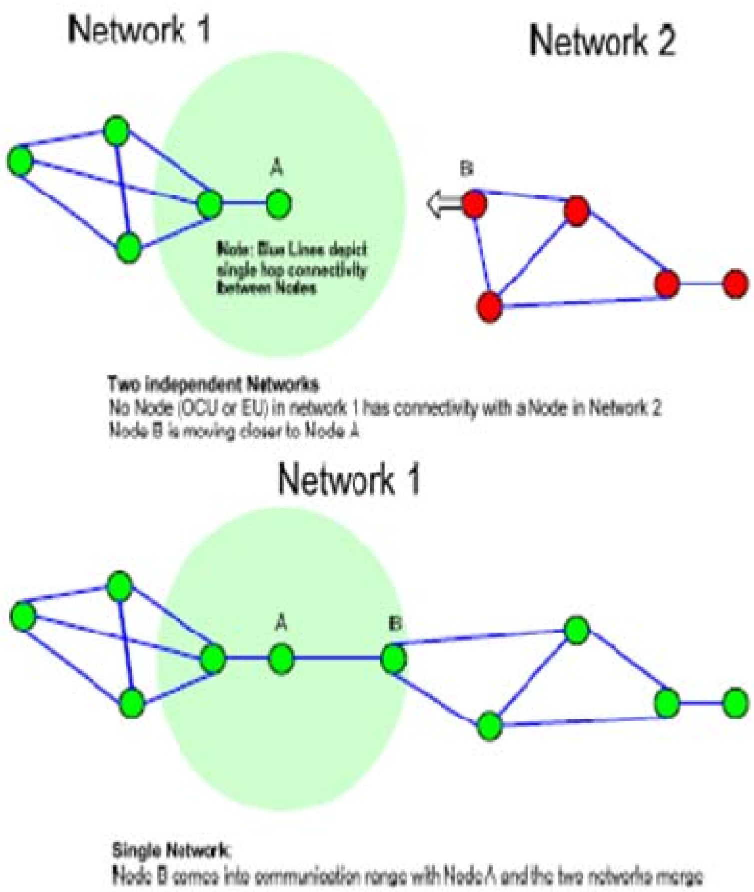

Figure 7. Network Split/Network Merge.[19]

Subsequent trials will show how a mesh network can enhance VBSS operations.

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[18] Trellisware. *TW220 Users Manual v1.3.,* 2008.

[19] Ibid.

III. LAND MANEUVER EXERCISES

A. BACKGROUND

Various experiments in 2008 and 2009 utilized the TW220 radios within the overall network for land maneuver exercises. This chapter details these experiments.

B. EMPIRE CHALLENGE 08

Joint Exercise Empire Challenge 08 (EC08) was conducted in July 2008. The purpose was to conduct two Joint Forces Command (JFCOM) J2 experiments to transfer biometric data, full motion video (FMV) through various obstructions, specifically a cave and a ship. This chapter discusses the research conducted during the cave simulation. The experiment was conducted with coordination from the Dod Biometric Fusion Center (BFC) and the Office of Naval Intelligence-National Maritime Intelligence Center (ONI/NMIC) for Biometric Intelligence Analysis Reporting (BIAC) development. The experiment was conducted at the China Lake Naval Air Weapon Station, Ridgecrest, CA.

Personnel from the BFC simulated biometric data much as a SOCOM team would collect suspected belligerents' data on the battlefields of Afghanistan and Iraq. Due to the sensitivity of the experiments, an unclassified database was used with volunteers entering their biometric data to be used for the experiment. The biometric data entered was personal information, iris data, and fingerprints. The data were the same input by operators in actual biometric gathering events. This information was sent to the BFC and input into an exercise database. Using matching technology, the researchers would take input from simulated suspects and send this data to the BFC through a mesh network. If successful, the information would be received by the BFC and compared to their database. If a match were found, a “detain” message would be generated. If no match were found, a “do not detain” message would be generated.

1. Network Topology

Cheetah radios were used inside the cave to transfer the biometric data into a Harris PRD 117G. These data were then sent via a wireless network to a COTS satellite system. The data were ultimately sent to NPS, BFC, and the ONI/NMIC. Figure 8 displays a diagram of the network.

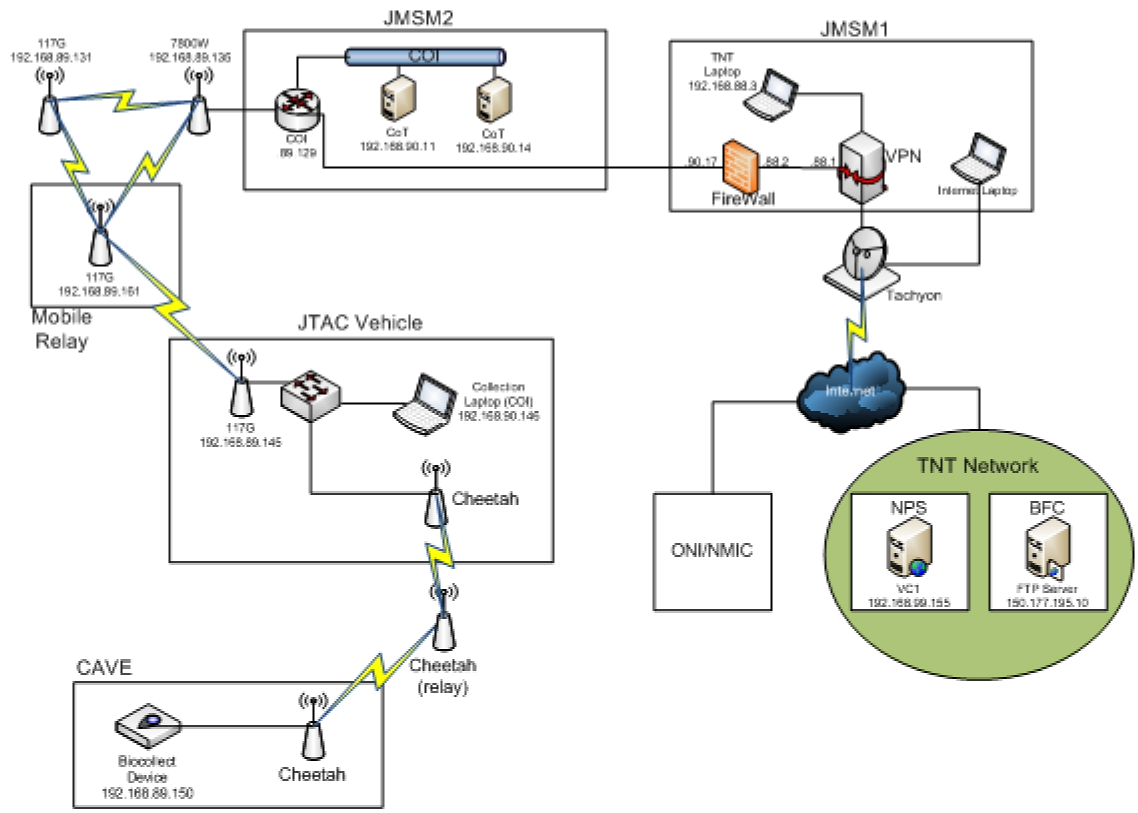

Figure 8. EC08 Cave Network Topology.[20]

2. Research Questions Addressed from EC08 Cave Experiment

The following is a summary of the original thesis questions answered by the EC08 Cave Experiment.

[20] Author/owner, *Summary Report of Cheetah Mesh-Networking Radios Used in the Biometric Experiments during Empire Challenge*, 2008.

- Research Area: Test the functionality of operational communication tasks through the merged network.
    - What is the quality of voice traffic on a merged network? This test was deemed unsuccessful. Various problems with Push To Talk (PTT) devices prevented voice traffic quality from being tested.
    - Can streaming video be passed over a merged network? Video was collected from inside the cave using an IP-based camera with a 5 megapixel array. TW220 data transmission rates caused the video to appear as still images. The usefulness of these images was deemed limited.
    - Can a data file be passed over the network and at what rate? Biometric data files were successfully sent via the TW220 radios over the network to the Biometric Fusion Center in West Virginia. The files were passed as Electronic Fingerprint Transmission (EFT) files to a File Transfer Protocol (FTP) site. Data rates were not tested during this experiment.

For MIO specific applications, the ability of the TW220 to merge, transfer data files and video images through arduous environments fulfills the requirements from Chapter I.

C. TACTICAL NETWORK TOPOLOGY (TNT) 08-2

The following exercise was conducted to demonstrate the feasibility of using the TW220 in Distributed Operations Tactical Command and Control (DOTC^2). This simulation can be compared with the Command and Control needs of a Special Operations team conducting any ISR mission.

> A group of Navy and USMC NPS students, under the guidance of LtCol Oros, teamed up with the Marine Corps Warfighting Lab in order to assess the operational feasibility of small handheld wireless networking devices (WND). The intent was to determine the self-healing/forming meshed-networking capabilities of the WND, and to specifically assess the network merging characteristics between multiple distant ground nodes in an Enhanced Company Operations (ECO) environment. Network joining experiments were conducted with both aerial and ground network relays.

> The experiment simulated small-unit ECO tasks in moderate to hilly terrain, similar to mission tasks associated with scout-sniper teams, ANGLICO teams, or infantry fire teams conducting satellite patrolling. The team successfully demonstrated network merging capabilities between four distant nodes (approximately 7.5 km apart) using the CIRPAS Pelican aircraft as an aerial relay. The network merging capabilities were also demonstrated with ground-based relays. Upon successful network merge, the team assessed the WND's on-the-move (OTM) multi-channel voice and data capabilities.[21]

The experiment did not place the TW220s into the overall TNT network. The TW220s used were the original prototype and the point was to ascertain how the SDRs interacted with each other and their ability to pass information from end to end.

During this experiment, the accessories used in conjunction with the TW220 were the following.

- Peltor Headsets: Tactical communication headsets currently used by U.S. Marines in operational environments
- Wildcat: Trellisware designed mobile, amplified unit that attaches a TW220 to a vehicle. The Wildcat amplifies the output power 10 watts.
- Omni-directional antennas: COTs antennas that can be vehicle mounted

Figure 9 shows the placement of each radio over the Camp Roberts testbed. Figure 10 demonstrates the differences in the elevation where radios were placed.

[21] Capt. Bob Price, *TNT 08-2 Quick Look Report* (Monterey: Naval Postgraduate School, 2008).

1. Network Topology

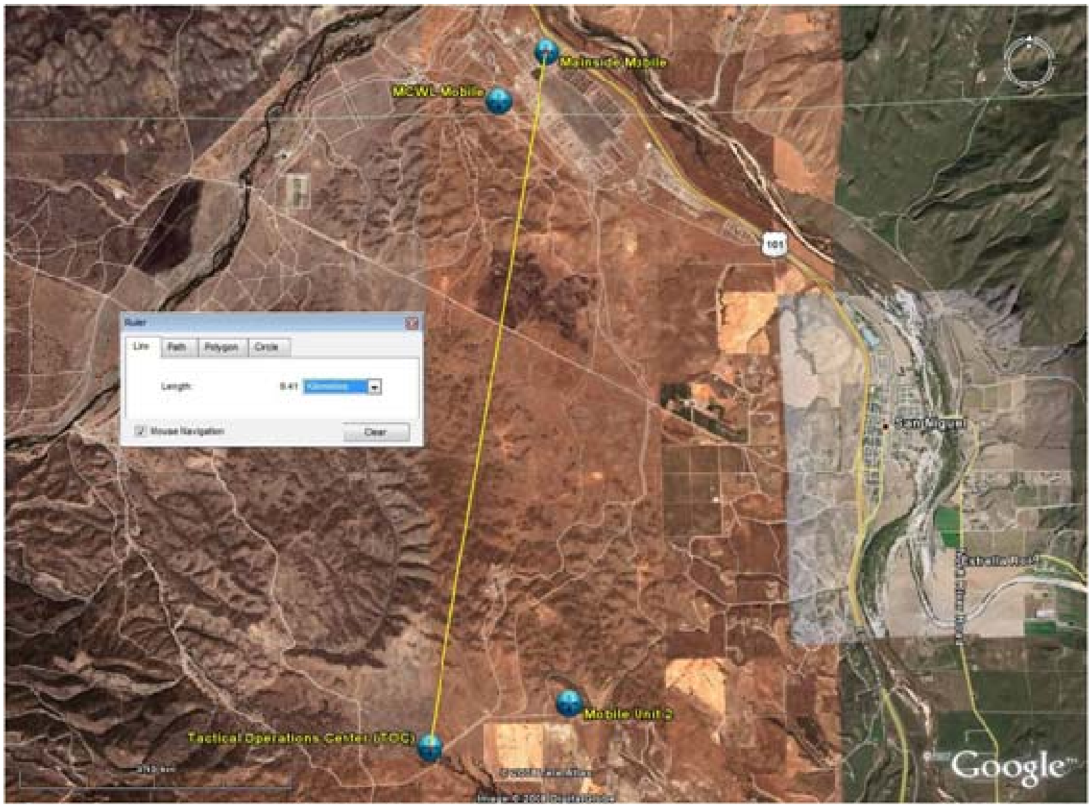

Figure 9. Ground Node Locations at Camp Roberts, CA[22]

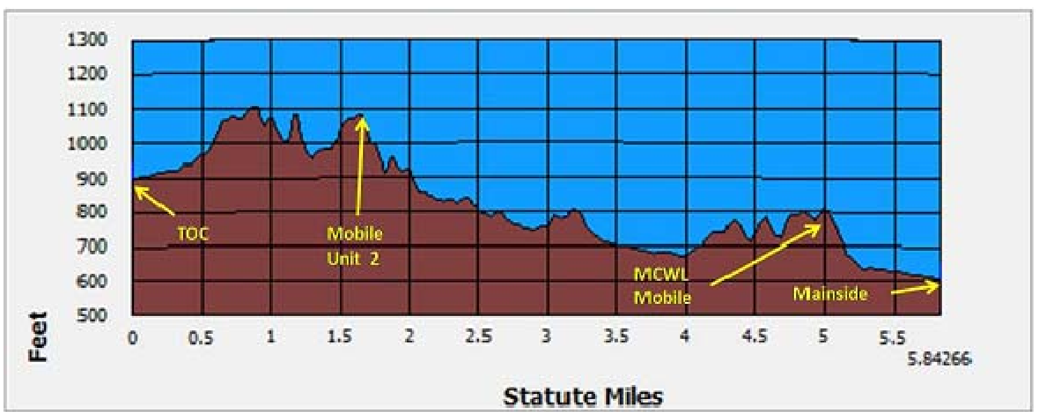

Figure 10. Elevation Differences for Different Nodes.[23]

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[22] Capt. Bob Price, *Distributed Operations Tactical Command & Control (DOTC2) Experiment. Tactical Network Topology 08-2 Experiment after Action Report* (Monterey: Naval Postgraduate School, 2008).

[23] Ibid.

2. Research Questions Addressed from TNT 08-2

From the TNT 08-2 After Action Report, the following questions and results are specific to this thesis.

- Research Area 1. The overall premise of the self-forming / self-healing capability and the network merging characteristics of the TW220.
    - Will a node that is introduced into the network be able to seamlessly join the network without any additional configurations or without disrupting the network? The test was deemed successful on both the ground and aerial relay. On-site baseline metrics were evaluated over a ground network relay of limited scope. The team conducted a network self-forming ground relay with the handheld TW220, though with intermittent connectivity. It was determined that the limited connectivity was due to terrain blocking features and lack of direct LOS. Network self-forming / self-healing aerial relay was successfully conducted during both flight windows. An aerial relay range of 18 km was demonstrated between the aircraft and the command node located at the TOC. The vehicle mount was used at the TOC and on the aerial platform. Network connectivity was established and voice and data services were extended from the TOC to the Mainside node (furthest node).
    - If a group of nodes within a network are moved out of range of the rest of the network, will they "self-heal" or form their own functional network? Or will they be individually isolated from the network and each other? This question was deemed successful. The first trial demonstrated that network self-forming / healing capability via ground relay, through network merge attempts via aerial relay employing a single handheld unit were unsuccessful. It was determined through lab testing that the result was due to "fill loss." It was demonstrated that if a TW220 is without a power source for an extended period of time (more than 12 hours), the unit must be completely zeroized, then reconfigured and reloaded with the encryption security keys. This phenomenon was observed on three separate occasions, one of which was conducted at the NPS lab. The TW220 used in the aerial relay was reconfigured and reloaded with encryption, but it was not zeroized. It is believed, had the aerial relay node been operational, connectivity would have been established via aerial relay, due to the range and frequency characteristics of the aircraft's flight pattern.

    - Will separate and independent networks composed of multiple nodes be able to merge when at least one node from a network comes within range of another network? Will both ground based and aerial relay enable this capability? The characteristics of the network merge capability were shown to be functional with the exception of one limitation identified during the ground network relay. The vendor identified a command node conflict, such that, once separate networks are merged or "healed," the newly designated command node did not relinquish its role to the original command node, resulting in competing command nodes. This behavior was corrected by using the vendor-provided network configuration manager to demote the original command node to a non-command node status. The vendor has corrected this error for future versions of the TW220.

As a note, a problem in data channel performance was also identified as the result of a time-dependent behavior error. This error manifested in the symptomatic behavior of data packet loss at regular time intervals. This error was replicated back at NPS and has been corrected by the vendor.

- Research Area 2. Test the feasibility of placing WND technology on an aerial platform.
    - Can a handheld unit be installed on an aerial platform to be used as a relay? The TW220 WND was successfully installed in the aircraft.
    - Can a vehicle-mount unit be feasibly installed on an aerial platform to provide aerial relay capability? The "Wildcat" vehicle mounted wireless network device was successfully installed on the aircraft.
    - What are the considerations and solutions to power requirements? Simple AC/DC power converters were fabricated using laptop power supplies and electrical wiring accessories purchased from Radio Shack.
    - What are the considerations for the installation of antennas, what type of antenna should be used, and what is the best position on the aircraft to optimize gain for the relay of ground networks? COTS multi-band omni-directional antennas were successfully employed and provided required gain for low-altitude aerial network relay. Installation of either form-factor could be easily replicated and improved for employment on UAV's.

- Research Area 3. Test the functionality of operational communication tasks through the merged network.
    - What is the quality of voice traffic on a merged network? Tactical voice communication was successfully demonstrated. Voice channel quality remained consistent and superior to conventional tactical radios.
    - Can streaming video be passed over a merged network? Steaming video was successfully demonstrated. Streaming video was transmitted over the network using Windows Media Encoder at a data rate of 128 Kbps, at a frame rate of 15 fps, and at a resolution of 320 x 240. Streaming video was transmitted over the network using Windows Media Encoder at a data rate of 93 Kbps, at a frame rate of 15 fps, and at a resolution of 240 x 180.
    - Can a data file be passed over the network and at what rate? A data file transfer was successfully demonstrated using Microsoft NetMeeting and Microsoft Windows FTP. A 548 KB file was transferred at data rate of 128 Kbps, and a 1.5 MB file was transferred at a rate of 75 Kbps. It is not certain why the 128 Kbps data rate for the 1.5 MB file transfer was not achieved, although it is believed to be the result of packet loss and retransmissions caused by the long-range link.
    - Can simple chat be performed on the network? Text chat was successfully demonstrated with NetMeeting and MIRC.
- Research Area 4. Test the overall range capabilities with regard to Command and Control capabilities.
    - What is the maximum operational ground range of the handheld version of the TW220 without a relay? Range between ground nodes was near LOS, although limiting terrain prevented definitive measurements.
    - What is the maximum operational ground range of the TW220 in the vehicle-mount configuration, without a relay? Again, the operational range was near LOS due to terrain limitations.
    - What is the maximum operational range at which the signal can be relayed employing an aerial platform? Range between the TOC and aircraft relay was measured at 18 km; however, this was also limited by blocking terrain.

As shown by these three results, absorptive terrain causes significant disruption to UHF frequencies.

- Research Area 5. Test management tool software application. How does the vendor-provided software management tool perform in a simulated operation environment? The functionality of the vendor-provided configuration management software proved adequate for the assessment requirements. A more user-friendly GUI must be developed to be practical in an operational environment.

Conclusion of performance: The results are based upon the TW220 handheld device versus a Single Channel Ground and Airborne Radio System (SINCGARS) currently being used by the Marine Corps. The Marine Corps does not employ hand-held or man-packed tactical communication systems with mesh-network capability.

- Relay/Retransmission
    - No need to configure relay nodes specifically. All nodes relay as needed.
    - Relayed traffic typically has insignificant loss of fidelity regardless of the number of hops.
    - Relays can occur over any number of hops (fixed at configuration time, currently at nine), while SINCGARS retransmission is only effective for one or two hops.
    - Only one radio needed for relay, while SINCGARS requires two radios using two frequencies.
    - Relay occurs on same channel. SINCGARS requires two channels, and a distant operator must manually switch to the retrans channel when connectivity is lost.
- Physical layer robustness
    - Not thoroughly tested in this experiment.
    - Better for urban and maritime operations (high reflectivity).
- Simultaneous voice and data
    - Each radio relays for channels it may not be using, and thus, transparent to user.
- Data and voice can occur simultaneously on same device without interfering with each other.

- Data rate: 128 Kbps is much better than the 16 Kbps available on SINCGARS radios.
- Two layers of encryption: Separate TRANSSEC and data keys would prevent leakage of information if a radio with only the TRANSSEC key were lost (for example, a relay node on a UAV). A radio can be loaded with only the data keys it needs (one per channel) and still retain all the relaying functionality.

The tests conducted during TNT 08-2 show that the capabilities of the TW220 can enhance MIO missions; specifically, the ability to merge, maintain voice, transfer video, transfer data, and maintain a secure network.

IV. MARITIME INTERCEPTION OPERATIONS

A. BACKGROUND

The following experiments were conducted to further test the TW220 in a maritime environment. Based upon previous land maneuver test results, the test bed was changed to large vessel and small craft environments. This chapter details these experiments and analyzes the performance of the TW220.

B. EMPIRE CHALLENGE 08

The second half of research for Empire Challenge 08 was conducted in San Francisco Bay. Six TW220 radios were tested to see if they could successfully form an ad-hoc mesh network to pass voice, video, and biometric data through the complex environments a large ship provides. This simulation is the equivalent of a VBSS team conducting a search onboard a large merchant ship underway.

The S.S. Jeremiah O'Brien was chosen for this experiment, which is a World War II Liberty ship. It is 450 feet long, with various watertight compartments and metal design that allows for testing the TW220's ability to take advantage of the reflective surfaces to enhance communications.

Figure 11 shows the diagram of the SS Jeremiah Obrien.

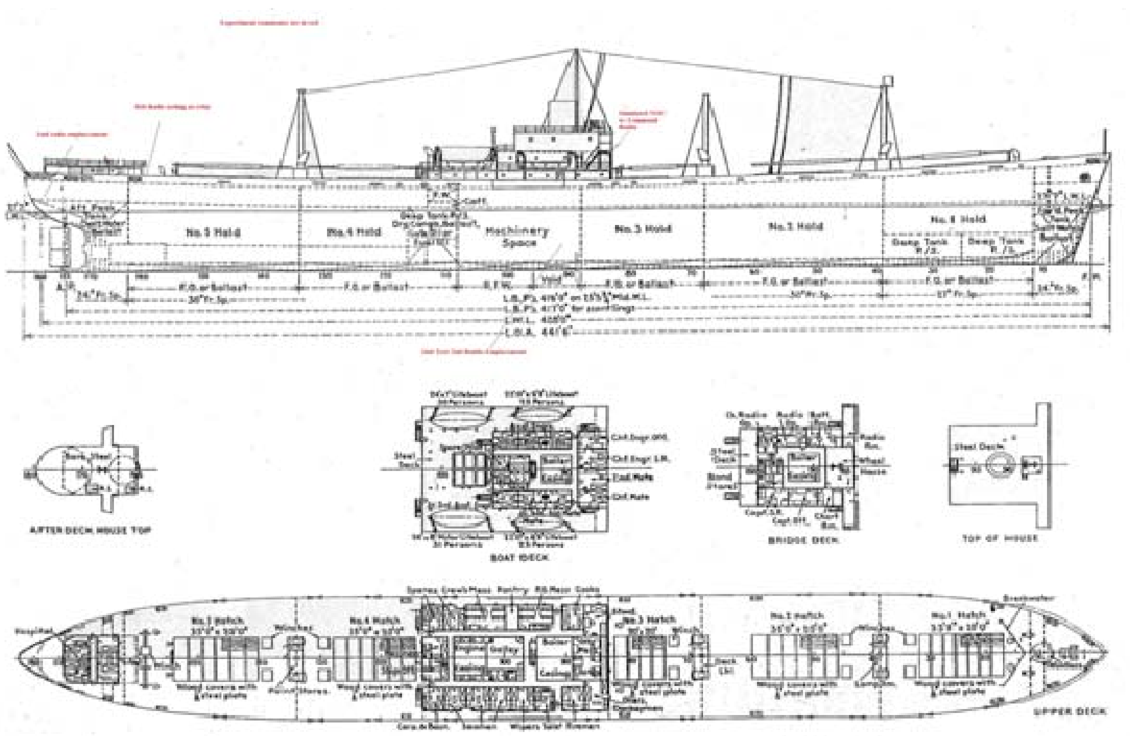

Figure 11. Liberty Ship Diagram.[24]

1. Network Topology

A TOC was set up in the ship’s wardroom approximately 200 feet from the farthest TW220 radio. From this point, the radios were inserted into the overall MIO network. Six radios were distributed at various locations between the TOC and ship’s after steering compartment. This space was utilized because it was the farthest point aft on the ship and would allow the testing of the radio’s ability to use reflectivity to maintain network continuity. The distance between the end node and the TOC was approximately 200 feet. Three radios were placed in between to serve as repeaters to transfer information between nodes. A fourth radio was placed in the engine room approximately 30 below the main deck. From this vantage point, an IP-based camera was utilized to test the ability to transfer video. The placement of the radios was to simulate boarding team members, as they would search a large merchant ship. The radios’ ability to join

[24] Project Liberty Ship, “Hulldeck,” http://www.liberty-ship.com/html/topics/hulldeck.html.

and leave the network would allow free movement of boarding team members while still maintaining connectivity between the end nodes in after-steering and the TOC radio plugged into the overall NPS network via a router. The data would be sent from the ship to other NOCs via the MIO-TNT 802.16 NPS network backbone. Figure 12 shows the overall network topology.

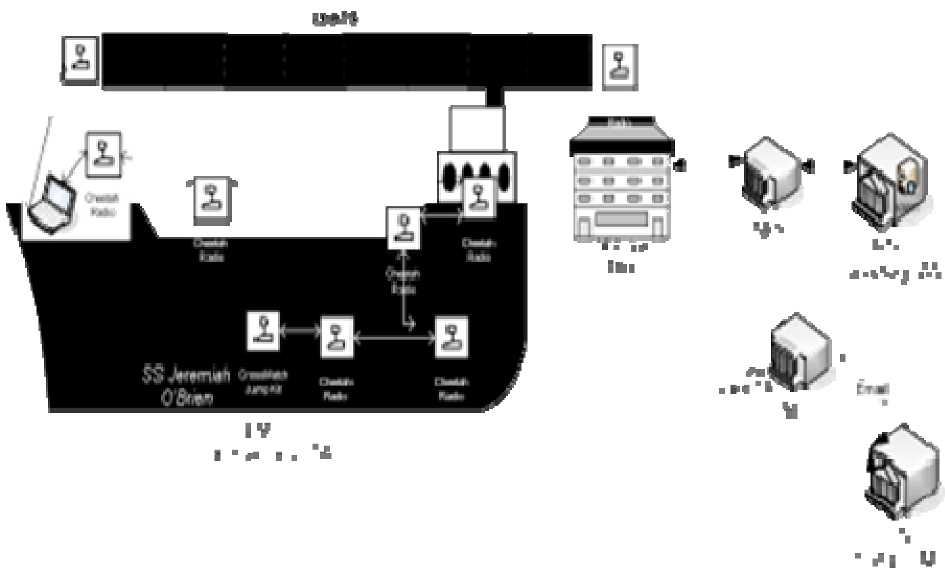

Figure 12. Network Topology for EC08 EMIO.[25]

2. Research Areas Addressed from EC 08 EMIO Event

- Research Area 1. The overall premise of the self-forming / self-healing capability and the network merging characteristics of the TW220.
    - Will a node introduced into the network be able to seamlessly join the network without any additional configurations or without disrupting the network? This test was deemed successful; five initial nodes were placed around the ship at various locations. A sixth node was introduced in the engine room and communications check was performed. No interruption of service was experienced.

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[25] Empire Challenge 2008 Summary Report.

- If a group of nodes within a network is moved out of range of the rest of the network, will they "self-heal" or form their own functional network? Or will they be individually isolated from the network and each other? This question was deemed successful. After adding the sixth radio, it was removed from the network. No network interruptions were recorded

- Research Area 2. Test the functionality of operational communication tasks through the merged network.

  - What is the quality of voice traffic on a merged network? Tactical voice communication was successfully demonstrated.

  - Can streaming video be passed over a merged network? Steaming video was successfully demonstrated. However, the video was at best considered still picture images.

  - Can a data file be passed over the network and at what rate? The test was deemed successful. Biometric data files (.bdf) were collected and uploaded via the HIIDE collection device to a laptop connected to the end node of the CheetahNet Network in the aft steering section of the ship. The files were transferred via VC1 chat, a collaboration chat tool developed by NPS. Each .bdf file is 785 Kb. From the timeline in the EC08 summary report, the time it took for the first file to be uploaded and transferred to the BFC FTP site was five minutes. At this point, the data were assessed and compared with known suspects within the BFC database in West Virginia. A "match / no match" assessment was made and was received back through VC1 and relayed to the boarding officer three minutes after the assessment was made from the other side of the United States. This experiment was using a fixed network infrastructure that allowed for a stable networking operating environment. However, this experiment shows that widely distributed networks can be used to bring operators directly in contact with subject matter experts from great distances.

  - Can simple chat be performed on the network? This experiment was deemed successful. All files and communication from remote locations were done using VC1 chat.

- Research Area 3. Test the overall range capabilities with regard to command and control capabilities.
  - What is the maximum operational range of the handheld version of the TW220 without a relay? Each TW220 was tested for tactical voice communication. The closest radio were 50 feet apart. The furthest node was three feet from the TOC in the wardroom. The ability to test communications between the end nodes by themselves was not conducted due to time restraints. Joe Utschig, NPS Research Associate, stated, "fewer radios may have successfully performed the task."
- Research Area 4. Test management tool software application. How does the vendor-provided software management tool perform in a simulated operation environment? Due to the lack of operator training and on-site vendor participation, the GUI provided for set up was cumbersome. Technical support was provided via phone between the vendor and boarding team members. This would not be practical in real-world operational environments.

The large vessel testing of the TW220 was deemed successful overall because the radios were able to merge, maintain voice, and transfer data and video.

C. MIO 09-4

"The specific goal for MIO 09-4 was to further explore new sensors, unmanned systems, networking, and situational awareness solutions for tagging, monitoring and interdicting small craft and their crews, possessing nuclear radiation threat and persistent detection and monitoring of Riverine activities."[26]

1. Network Topology

TW220 radios were employed by boarding officers to communicate voice between craft on the James River and the NOC located at Ft. Eustis Virginia.

Figure 13 shows the overall network diagram.

[26] Author/owner, *Tactical Network Topology 09-4 After Action Report* (Monterey, Naval Postgraduate School, 2009).

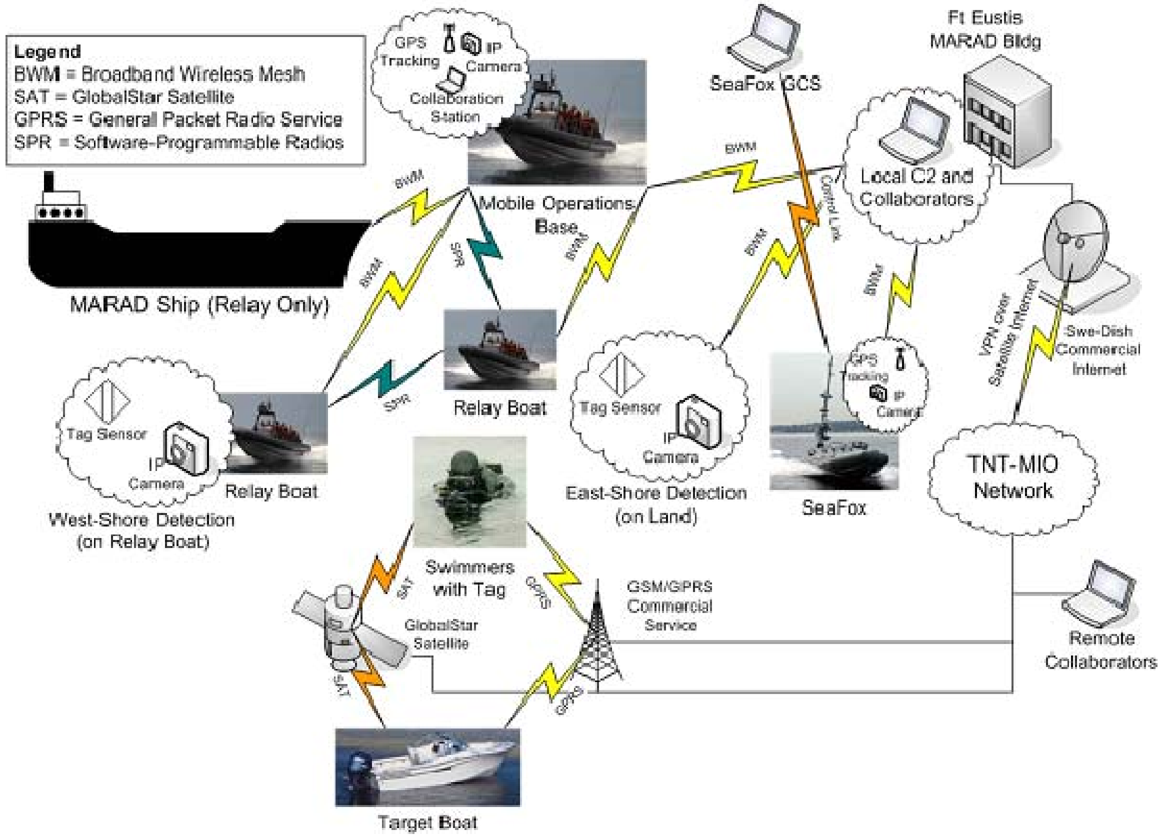

Figure 13. Ft. Eustis Network.[27]

TW220 radios are depicted as SPR in the above diagram.

Figure 14 shows an aerial view of the overall operational area at Ft. Eustis, VA.

[27] Author, *Tactical Network Topology 09-4 After Action Report*.

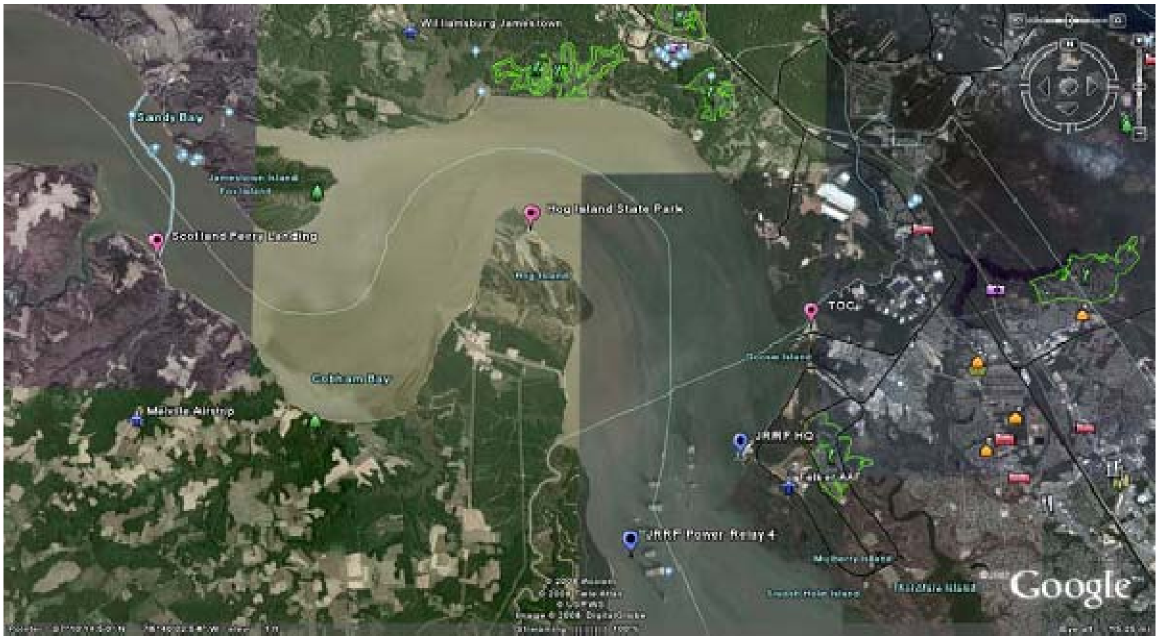

Figure 14. Ft. Eustis Area of Action.[28]

Figure 15 shows the TW220 relaying video to the TOC located ashore at Ft. Eustis.

[28] Author, *Tactical Network Topology 09-4 After Action Report*.

Figure 15. TW220 on Interdiction Craft Demonstrating the Ability to Send Video from Onboard Camera.

2. Research Questions Addressed from TNT 09-4

The fast craft chase provided the opportunity to test the ability of the TW220 to maintain voice communication on small boats exceeding speeds of 55 knots and the ability to maintain a GPS link at high speeds.

- Research Area: Test the functionality of operational communication tasks through the merged network.
    - What is the quality of voice traffic on a merged network? Tactical voice communication was successfully demonstrated between the shore based NOC and interdiction vessels as long as all nodes were within line of sight of each other. Small boat testing within the river basin was maintained within line of sight as well. Once the small craft was out of LOS, communications were lost between the

NOC and small boats. An aerial relay would have been helpful to maintain communications. Voice communication was maintained between the small boats at high speed.

- Can streaming video be passed over a merged network? Video streaming was successfully demonstrated between the interdiction boats and the NOC.
- Can GPS information be successfully downloaded to the TW220 radio? GPS data was successfully generated within the TW220s at high speeds onboard the interdiction crafts. Information was accurate for latitude, longitude, and speeds. Speeds demonstrated were in excess of 50 knots.

The results of this experiment conclude that the TW220 can used to satisfy the following requirements in small craft interdiction exercises. The TW220 was able to maintain voice connectivity, video transfer, and accurately depict GPS data while conducting high-speed maneuvers.

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V. CONCLUSION

A. NECESSITY FOR COTS SOLUTIONS

The experiments contained in this thesis have shown that COTS technology can be combined together to enhance military operations. The TW220 have shown to be successful in passing voice, video, GPS, and data seamlessly from the user by bringing subject matter experts and operators closer together. VBSS or SOC Teams did not utilize handheld devices possessing the ability to pass all the necessary information successfully that could allow operators to perform more efficiently and safely. JTRS has yet to be implemented fleet wide while a need still exists for the capabilities this technology provides.

U.S. armed forces use outdated technology combined with stove-piped systems that do not interact with one another in a plug-and-play environment. Handheld radios are still used to communicate voice transmissions between team members and their on-scene commander. That information is then relayed up through the chain of command via antiquated voice communications from ship to satellite or passed over the ship’s network via chat.

Photos of individual suspects are taken using stand-alone digital cameras. The boarding teams must bring these photos back to their home base to be disseminated up the chain of command to be relayed to various agencies that are literally thousands of miles away. The time to process this information can take hours to literally days before it can be analyzed and returned to the on scene commander to determine if the photo was of an individual who should have been retained.

VBSS and SOCOM teams are utilizing biometric collection devices for gathering intelligence on possible suspects. These devices perform retina scans, and collect fingerprint and individual data on each suspect. This information is loaded and stored in a database within the collection device and is then transported back for dissemination to various intelligence agencies.

MIO team members still have the need for technology that is inclusive and can do the following.

- Research Area 1. Tactical Voice Communication—The ability for all team members to be able to communicate with one another and with the Officer in Tactical Command (OTC).
- Research Area 2. Video—The ability for each team member to send video back to the entire Chain of Command (COC) as they are conducting a search of a suspect vessel. An example would be a USCG team searching for nuclear devices upon a large merchant vessel at sea. Not all boarding team members are subject matter experts. The ability for the team member to be able to show experts visually, such as those employed to identify known threats, would greatly enhance the effectiveness of the overall operation.
- Research Area 3. Data—Biometric data is collected in individual files within collection devices. This data must be transported back to a NOC to be disseminated to various government agencies for database entry and identification. Time could be saved by automatically sending the data to these agencies as soon as they are collected. Other examples of data files that must be transferred are ship’s manifests, crew logs, and pictures of individual crew members and suspect cargo.
- Research Area 4. Personnel Location—An added safety consideration would be the ability to track boarding team members as they search a large merchant vessel. An OTC would have greater situational awareness of each team member’s location within a suspect vessel.
- Research Area 5. Simplicity in design—Small handheld devices would greatly diminish the amount of equipment that VBSS teams must bring aboard a suspect vessel. A durable waterproof design that is intuitive to operate would be beneficial to overall operations.

B. SUMMARY OF EXPERIMENTS

EXPERIMENT	VOICE	DATA	VIDEO	CHAT	GPS
EC Cave	Untested	Successful, Biometric data was uploaded and relayed across the network	Marginal Video produced was the equivalent of still .jpg	Chat was successfully demonstrated using VC1 chat room	Untested
TNT DODTC	Successful, Tactical Voice Communication was established and maintained within LOS	Successful, Files were transferred between nodes using FTP	Successful, Streaming video was passed at 128 KBps	Successful, Ability to chat between laptops was demonstrated	Untested
EC Large Craft	Successful, Tactical Voice Communication was established and maintained	Successful, Files were transferred between nodes using FTP	Marginal Video produced was the equivalent of still .jpg	Chat was successfully demonstrated using VC1 chat room	Untested
TNT MIO 09-4	Successful, Tactical Voice Communication was established and maintained	Untested	Successful, Full streaming video was able to be transmitted within LOS	untested	Marginal, GPS data could be read from TW220 at high speeds; however, the Google Earth Application was untested.

Table 2. Overall Results TW220 Experiments

The overall testing of the TW220 shows that it demonstrates the capabilities a MIO boarding team must incorporate into their networking capabilities.

A requirement still exists for a more robust unit that is more intuitive to a military operator. Also necessary is for the abilities to be configured without the use of a Network Operations Center. The ability to configure the radios in the field would greatly enhance the ability of operators in remote areas to troubleshoot and repair should the need arise.

C. FUTURE RESEARCH

1. Expansion of TW220 in a MIO Environment

Utilizing the TW220 as the primary communications device, a simulated boarding of a large merchant vessel combined with small craft operations should be conducted. The TW220s could possibly be integrated with the following networking solution.

- Tactical Cellular
- Ultra Wide Band (UWB)
- Multiple Input / Multiple Output (MIMO)
- Network-Controlled Robotics (Unmanned Vehicles)

2. Possible Combination of TW220 and Small Satellites

Software defined radios could be embedded into low earth orbiting satellites, as well as if the radios could be combined with other plug-and-play technology that would allow the synchronous communication between the radios and the satellite to further project the network footprint.

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